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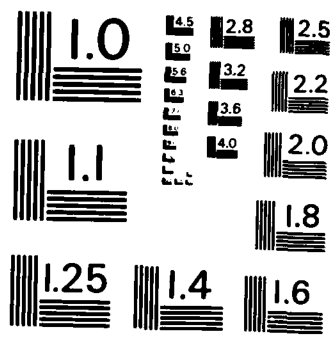

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A COMPARATIVE EVALUATION OF THE RELIABILITY IMPROVEMENT IN LINE REPLACEABLE UNITS WARRANTED UNDER THE F-16 RELIABILITY IMPROVEMENT WARRANTY

THESIS

Stephen J. Lemke
Captain, USAF

AFIT/GLM/LSP/85S-44

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THESIS

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology
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Master of Science in Logistics Management

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Abstract

This ~~investigation~~ thesis examined the effects a reliability improvement warranty (RIW) had on the actual operational reliability of the warranted avionics equipment. To accomplish this, the most comprehensive DOD application of RIW to date, the F-16 RIW, was investigated. This study was designed to answer the question of whether or not a warranted → weapons system was significantly more reliable than it would have been without the warranty. Specifically, the observed mean flight hours between failures (MFHBFs) and the observed reliability growths of the warranted F-16 equipment were compared to those of functionally similar non-warranted F-15 equipment. Also, the reliability growth of the F-16 warranted equipment was compared to that of other non-warranted F-16 equipment. The AMSAA Reliability Growth Model was used as a basis for the reliability growth analyses. Comparable life cycle time periods for each aircraft were studied, using AFM 66-1 DO56 failure and flight time data.

The results of the investigation indicated that, in general, the observed MFHBFs of the F-16 warranted equipment were statistically greater than the MFHBFs of the equivalent F-15 equipment. The same could not be concluded for the

reliability growths of the F-16 and equivalent F-15 equipment. However, the reliability growth of the warranted F-16 equipment was found to be statistically greater than the reliability growth of the non-warranted F-16 equipment. The study concluded that the observed increased reliability and reliability growth rate of the warranted F-16 equipment, was due, at least in part, to the F-16 RIW.

A COMPARATIVE EVALUATION OF THE RELIABILITY IMPROVEMENT IN LINE REPLACEABLE UNITS WARRANTED UNDER THE F-16 RELIABILILTY IMPROVEMENT WARRANTY

I. Introduction

Overview

Weapon system quality, reliability, and availability are obviously major concerns of the Air Force, especially since our systems have become extremely complex in recent years. Within just the past three years, reliability and supportability have become very important issues in the Department of Defense (DOD) system acquisition process. An increase in system reliability, along with the corresponding decrease in supportability costs, can be viewed as the primary factors responsible for lowering operating and support costs, the largest portion of the system's total life cycle cost. Reliability and supportability were two of the significant issues addressed in the "consolidated" Defense Acquisition Improvement Program initiatives introduced in 1983 by the Deputy Secretary of Defense, Paul Thayer (1:11; 2:9). This high level concern for increased reliability and supportability, along with the ever increasing spending constraints put on the Air Force by Congress (3), are two of the driving factors that have influenced DOD to explore contract reliability and supportability assurances for use in the acquisition process.

Probably the most prevalent among these assurances is the warranty, and more specifically, the reliability improvement warranty.

In late 1983, the interest in warranties was elevated to the congressional and presidential levels with the passage of Section 794 of the 1984 DOD Appropriation Act (2:9; 4:14; 5:44). This bill required that performance warranties be procured for all weapon systems, unless waived by the Secretary of Defense for national security reasons or if the required warranty were not cost-effective (2:9; 5:44). Needless to say, this high level congressional interest makes the subject of warranties a major concern for the DOD.

A warranty is "a promise that certain facts are truly as they are represented to be and that they will remain so, subject to any specified limitations" (6:1423). Through a written warranty, the supplier promises that the "material or workmanship is defect free or will meet a specified period of time" (6:1424). One of the purposes of the warranty is to protect the buyer, or in this case, the government, against defects that cannot be detected prior to purchase and that only become apparent after the system has been used. It thus gives the government an increased time period to assert its rights. The Federal Acquisition Regulation (FAR) defines a warranty as

> a promise or affirmation given by a contractor to the Government regarding the nature, usefulness, or condition of the supplies or performance of services furnished under the contract. The general

purposes of a warranty in a Government contract are (1) to delineate the rights and obligations of the contractor and the Government for defective items and services and (2) to foster quality performance (7:46-9).

The warranty is actually a subset of a larger class of product assurances, called product performance agreements. The Product Performance Agreement Guide, developed jointly in 1979 by senior Air Force and industry representatives, lists 23 different types of product performance agreements, eight of which are directly called warranties, in one form or another (8:Part B). In general, the intent of product performance agreements is to provide an incentive for the contractor to enhance both the performance and supportability of his product "during interim contractor support before transitioning into organic support" (9:26). The underlying assumption is that the contractor will be motivated not only to develop a high quality product, but also to continually improve that product's reliability and supportability throughout its functional life. The bottom line is that this increased system reliability should reduce the life-cycle costs by reducing the largest part of the total cost of ownership, the operating and support (O&S) costs.

If the volume of literature is proportional to the frequency of use or dollars involved, then the reliability improvement warranty (RIW) is by far the most popular product performance agreement used by the DOD in the recent past. The RIW is used to provide an incentive to the contractor to design and produce systems with increased reliability and reduced repair costs (10:3-1; 11:1). For this, the government pays an agreed upon fixed price, while the contractor agrees to repair or replace, if required, the failed, warranted systems returned to his facility, at no further cost to the government. The RIW contract is normally awarded concurrently with the production contract (10:3-1). The contractor is highly motivated to provide a highly reliable and supportable system because of the fixed price nature of the RIW contract - the more he can reduce the repair costs, the more profit he can realize (11:3). Under this concept, the contractor can further improve system reliability or supportability during production through engineering change proposals (ECPs), again at no additional expense to the government (10:7-38; 11:3).

In its pamphlet, Interim Guidelines - Reliability Improvement Warranty (RIW), the Air Force Directorate of Procurement Policy estimates that most increases in reliability as a result of a RIW will occur in the initial years after the system's deployment (11:4). It also states that "after the equipment's reliability and maintainability have been satisfactorily demonstrated through field use", the Government may evaluate the RIW's effectiveness (11:4). With this point in mind, in 1983, Parkinson and Schoolcraft concluded that very few studies have ever really been undertaken to determine RIW effectiveness for DOD applications (12:5).

Problem Statement

During the mid to late 1970s and early 1980s, DOD procured numerous weapon system components using the RIW concept. A review of the literature indicated that apparently very few RIW programs have ever been assessed for their cost effectiveness (through reliability improvement) at the completion of the warranty. Very few research studies have ever evaluated the RIW in terms of whether or not it actually caused an increase in a warranted system's reliability. Since this acquisition approach has the potential for achieving increased reliability as well as economical supportability, and since warranties, in general, are now subjects of high level congressional and DOD interest, there is an important need to evaluate the effectiveness of RIW..

Background

Introduction. The DOD major weapon system acquisition process in the past typically emphasized initial acquisition cost, schedule, and system performance, but not reliability and supportability. Because of this lack of emphasis, "past failures to meet reliability goals have resulted in decreased performance capability, increased maintenance costs, more expensive spare parts procurements, and costly product improvement efforts" (13:20). Only within the past ten years, with the advent of integrated logistics support, has design reliability and supportability been given equal consideration with cost, schedule, and performance. But how does the DOD motivate the contractor to design reliability and supportability into the system, especially when it is to the contractor's advantage to deliver the lowest design reliability the DOD will accept? For, by increasing system reliability the contractor increases "his manufacturing and quality-control costs" and reduces "his opportunity for sale of spare units, service contracts, and replacement parts to provide operational support" (14:2-2).

This need to provide a contractual incentive to improve reliability led to a new type of warranty contract - the reliability improvement warranty (RIW). A RIW is defined as

> a provision in either a fixed price acquisition, or fixed price equipment overhaul contract in which: (a) the contractor is provided with a monetary incentive, throughout the period of the warranty, to improve the production design and engineering of the equipment so as to enhance the field/operational reliability and maintainability of the system/equipment; and (b) the contractor agrees that, during a specified or measured period of use, he will repair or replace (within a specified turn-around time) all equipment that fails (subject to specified exclusions, if applicable) (11:5,6).

The RIW is thus a fixed price contractual provision which motivates contractors to both design and produce systems with inherently low failure rates and repair costs, and improve system reliability even after the system has been deployed. The primary objective of the RIW, then, is to achieve an increase in reliability, even though the major expense of the RIW contract covers the anticipated repair services (14:2-5). Before the advent of the RIW, the risks associated with deploying state-of-the-art technology rested squarely on the shoulders of the Air Force. Poor reliability brought on "high O&S costs or reduced asset availability" (10:3-2). With RIW, however, the risks are shared by both the Air Force and the contractor.

The mean time between failure (MTBF) guarantee is often used in conjunction with a RIW (9:26; 10:3-2; 15:20). Again, it provides an incentive for the contractor to increase reliability and reduce support costs. The MTBF guarantee requires the contractor to institute some kind of corrective action (modifications, engineering analyses, ECPs) if the warranted systems fail to meet the contractually specified MTBF (16:7,8). It also requires the contractor to provide the government additional spares to support its normal operations, as outlined in the contract (10:4-2; 16:8).

As stated earlier, under a RIW the contractor should be highly motivated to provide a highly reliable and supportable system because of the fixed price nature of the contract - the more the contractor can reduce equipment failures and their accompanying repair costs, the more profit he can realize. "He has a strong incentive to achieve or exceed the reliability level on which the warranty price was based" (14:2-5). There is also a strong incentive for the contractor to further improve system reliability through no-cost ECPs and production changes, especially during the initial stages of the warranty (10:7-38; 14:2-5). Obviously, since profit is a strong motivator for the contractor, it is unlikely that he would introduce no-cost ECPs during the latter stages of the warranty period, especially if the expected savings in repair costs is less than the costs he would incur to make the change. In fact, in an Air Command and Staff College research report on contractor RIW incentives and risks, Major Raymond Hudkins concluded that no contractor saw any real incentive to introduce RIW ECPs "after two years into a five year RIW" (17:98). Perhaps the real incentive for the contractor to improve design reliability and thereby reduce supportability costs starts by "stating in the development contract that a warranty will be a requirement in the production contract" (18:2).

Before discussing the RIW in detail, a review of the concepts of reliability and reliability growth is in order.

Reliability and Reliability Growth. Certainly the importance of weapon system reliability can never be overstated; it provides the probability that the system will successfully carry out its mission. From an economics viewpoint, the higher the reliability, the greater the likelihood that major cost savings can be realized over the life of the system. Typically, a system's life cycle is made up of three distinct failure phases: an early failure period, a random failure period, and a wear-out failure period (19:8). During the early failure or burn-in period, failures normally occur because of faulty designs, faulty manufacturing, or inspection deficiencies (19:8). It is during this early phase that design improvements are normally made, "product tolerances are reduced," and manufacturing operations are streamlined (20:11). During the second phase, the random failure period, "systems experience chance failures according to one of the several probability distributions, normally the exponential" (20:11). The last phase, or wear-out period, is characterized by an increasing failure rate due to the deterioration of the system components.

Reliability is directly related to the life cycle cost of a weapon system. System reliability improvements incorporated during the design stage cost the government considerably less than reliability modifications made during later stages in the life of the weapon system. Thus, "it is desirable to have intensive research and reliability engineering in the design phases, rather than after a weapon system is in the operational inventory" (20:12). Realistically, for one reason or another, this intensive infusion of reliability into the design phase has not occurred. Therefore, nearly all weapon systems experience a reliability improvement phase known as reliability growth.

Reliability growth is the "positive improvement of the reliability of equipment through the systematic and permanent removal of failure mechanisms" (21:3). It is not a naturally occuring characteristic of electronic equipment (22:12); it requires a conscious engineering effort to attain higher levels of reliability through the elimination of design weaknesses. Reliability growth can take place at any point in the system's life cycle. Again, the earlier in the life cycle it occurs, the less it will cost.

Reliability growth can occur in one or more of the following three ways (22:6):

1. Through the operation of the equipment, defective components or manufacturing faults can be exposed and replaced.

2. Through familiarization, the operators become more skilled at operating the equipment.

3. The discovery of "errors or weaknesses in design, manufacturing, or related procedures" lead to their correction. In this case the failure mechanism is permanently removed.

The concept of reliability growth plays a very important role in the RIW decision process. The cost effectiveness of any RIW is a function of the reliability growth expected to take place over the warranty period (23:235), in addition to the incentive the RIW provides for a reliable design.

<u>RIW Historical Background</u>. The use of warranties in defense contracts is not new. The Armed Services Procurement Regulation (ASPR), in 1964, contained specific guidelines for the use of warranties in firm-fixed-price contracts. As instructed by the ASPR, warranties were only to be used when the warranty protection afforded the government was greater than the cost of the warranty (24:4). At that time DOD used

warranties mostly for "the procurement of small, off-the-shelf items" (25:2). Then in 1967, a "correction of deficiency" clause was added to the ASPR, which essentially attempted to hold the contractor responsible for the design and quality of his product. It required the contractor to "correct or repair defects discovered in items delivered to the government under that contract" (25:10). The Navy was really the first service to apply the warranty on a significant contract. It used a failure free warranty (FFW) type of contract for the overhaul of gyros. The FFW was, in effect, the forerunner of the RIW (24:3). The Air Force followed suit in 1969, with the award to Lear Siegler of a contract for the acquisition of attitude and heading gyros which contained a FFW (24:4). For the next ten years the services awarded very few additional major contracts containing warranty clauses. During the mid-1970s, however, numerous warranty studies gave rise to the reliability improvement warranty concept, and the RIW became a high level issue in DOD. With the publishing of the DOD pamphlet containing RIW guidelines in 1975 (Interim Guidelines - Reliability Improvement Warranty (RIW)), the military services were "to undertake a trial use of RIWs in a number of electronic system/equipment programs" (24:5,6).

Since 1975, the use of warranties (especially RIWs) in Air Force acquisition programs has increased significantly. For instance, in 1979 there were 44 programs with some sort of warranty or incentive clauses in their contracts (24:7), and according to the Deputy Under Secretary of Defense for Acquisition Management, Mary Ann Gilleece, in 1979 "one-third of our 4.1 million types of items in inventory were covered by some form of warranty" (9:26). During the late 1970s, RIWs were applied to the following Air Force production contracts: the ARN-118(V) TACAN, the C-141/KC-135 inertial navigation system, the C-141 heading system, an F-111 gyro system, and nine components of the F-16 (17:2). And these represent only a few of the RIW contracts used at that time. Of these, the F-16 RIW program, the focus of this thesis, was the "most comprehensive and complex application of RIW ever attempted" within DOD (10:1-1). The RIW contract was between the Air Force and General Dynamics, but General Dynamics, in turn, applied the contract to four of its major avionics subcontractors (26:103). This leads to the present, where the interest in warranties has been elevated to the congressional and presidential levels.

In late 1983, Congress passed the 1984 DOD Appropriation Act. Section 794 of that Act, authored by Senator Mark Andrews of North Dakota, required performance warranties for all DOD weapon systems (2:9). Waivers may be provided by DOD for national security reasons or if the required warranty were not cost-effective; however, such a waiver must be reported, in writing, to four separate House and Senate committees (5:44). After much debate and a lot of pressure from the defense community, several revisions were made to the law, giving DOD more flexibility in using warranties; they are included in the recently signed 1985 Defense Authorization Bill (27:24).

RIW Advantages Versus Disadvantages. As might be expected, warranties have benefits as well as negative aspects. The government and the contractor are not necessarily at opposing ends of the issue, though. What is an advantage for the government may not always be a disadvantage for the contractor. While the literature refers to numerous RIW advantages and disadvantages, this review included only the most relevant and the most often cited aspects. The majority of these positive and negative aspects should be classified as perceived or intuitively obvious, since it appears from a review of the literature that very little empirical research has been conducted on the actual effects of the RIW in government contracts.

The following advantages the government can expect actually deal with one aspect - the reduction of system life-cycle costs. Under a RIW, the program risks as well as the rewards are now shared by both the government and the contractor; the government has more time to uncover design or production defects not readily apparent at the time of delivery (10:3-2). A second government benefit is that the contractor has the incentive to provide a highly reliable system with low support costs, which ultimately results in reduced system life-cycle costs. The contractor is also motivated by a potential increase in profits to improve the system reliability and supportability after production. He does this through design improvements at no cost to the government (10:3-1,2; 25:2). Another benefit to the government is that the cost of ownership during the warranty period is fixed to a degree, since any repairs will be covered by the warranty; this reduces the need for future program dollars for repairs (25:18; 2:10). One last important benefit is that design and production deficiencies are discovered early on and not perpetuated "into on-going production or into new systems under development" when warranted equipment is returned to the contractor for repair (26:103).

Probably the most important benefit to the contractor is the possibility of increased profits. Very simply, if the contractor's actual repair or replacement costs plus his administrative costs for warranty service are less than the amount paid by the government for the warranty, he earns a profit (8:10). Another benefit to the contractor is the "opportunity to receive feedback on equipment operation" in its operating environment (17:31). This knowledge may be invaluable for his future designs or even more importantly, for design or production changes during current production runs.

The potential RIW disadvantages to the government are numerous. First of all, acquisition costs will certainly increase - without exception, warranties cost money (9:26).

Additionally, it is extremely difficult to accurately predict the future costs and benefits that are expected to be the result of a warranty. Because of this limitation, most of the costs are derived from nothing more than educated guesses. Another disadvantage is an increase in administrative complexity. The RIW administration involves added record keeping, reporting, and increased monitoring (10:7-31). Mary Ann Gilleece points out another potential RIW disadvantage which results when the contactor changes a system defect or improves a system supportability aspect under the warranty. The problem is that, unknown to the contractor, this design change could possibly require resultant changes to interfacing systems such as support equipment (9:26). So while the system repair costs may be reduced by this design change, the overall costs to the government may actually increase due to expensive changes required in the support equipment. Another problem arises when a warranted system fails. Under almost all RIW contracts in the past, Air Force maintenance personnel were only able to do fault isolation and other similar tests on failed equipment. They had neither the "tools" nor the expertise to repair the the defective, warranted equipment; they could only replace it and send it to the contractor (10:7-3). This type of maintenance support concept would obviously be unacceptable in combat situations. Also, additional training would be required for maintenance personnel to preclude them from voiding the warranty through improper maintenance actions. Especially in light of recent attempts to increase competition in the acquisition process, one last disadvantage is that the requirement to have a warranty included in a contract may actually be detrimental to small businesses. They normally have only limited resources to back up the warranty (5:44).

Many of the above RIW disadvantages also affect the contractor. It is just as difficult for the contractor to accurately predict the future costs, failure rates, etc., as it is for the government. The shared-risk advantage to the government becomes a disadvantage to the contractor. "Mishandling or improper use" of warranted equipment by Air Force personnel may cause failures which are beyond the control of the contractor (2:10).

The F-16 RIW Program

Contractual Background (28). The F-16 production contract (F33657-75-C-0310) contained a special provision, J.63, which left the option open to the government of including a RIW and a RIW with a MTBF guarantee in the final contract. In 1975, the government negotiated with General Dynamics to exercise this option on U.S. F-16s to include the coverage of 12 line replaceable units (LRUs). Near the end of 1975, the European Participating Governments (EPGs) expressed the interest to exercise the RIW option, also. (The F-16 program is a multi-national fighter program - the countries involved are Belgium, Denmark, The Netherlands, Norway, and the U.S.)

During 1976, the U.S. conducted economic analyses on the RIW covering the 12 LRUs. In October of that year, negotiations were reinitiated with General Dynamics to extend RIW coverage to the four EPGs as well. The initial RIW price for the EPGs alone was determined to be prohibitive, so the Air Staff approved a combined U.S./EPG RIW program. Negotiations were completed in February 1977 with the signing of a separate RIW contract (F33657-77-C-0062) for the coverage of nine LRUs for all five nations, with a not-to-exceed cost of $44 million. Later that year General Dynamics submitted a definitization proposal for the RIW contract which identified numerous conditions of cost. The government rejected 14 of these cost conditions, which resulted in further negotiations and fact finding during 1978 and early 1979. The RIW started in January 1979, even though the contract was not finalized. In May 1979, the F-16 Contracting Officer issued a final decision after negotiations were discontinued. In September, General Dynamics appealled the decision to the Armed Services Board of Contract Appeals (ASBCA). With the Air Force response to the ASBCA in April 1980, it was obvious no settlement could be reached. The two parties would go to court; pre-trial hearings began in September of that year in Washington, D.C. Before the case was settled in court, the decision was made on 20 March 1981 to commence out of court settlement negotiations. General Dynamics and the Air Force finally reached a settlement in April. The Air Force compromised on several of the cost conditions, however the not-to-exceed cost remained at $44 million.

<u>Program Description</u>. The F-16 program included nine of the original twelve LRUs and applied to the first 250 USAF and first 192 EPG production F-16s delivered, and their associated spares (10:4-1). The nine LRUs covered and their manufacturers included the following (10:4-1; 26:103):

APG-66 Radar (five major LRUs) - Westinghouse

Head-up Display (two major LRUs) - Marconi Avionics

Inertial Navigation Unit - Singer-Kearfott

Flight Control Computer - Lear-Siegler

The radar transmitter and the head-up display electronic unit were also covered by a MTBF guarantee. The warranty period lasted four years, from January 1979 to December 1982. The warranty actually covered a four year period or a combined total of 300,000 flight hours on the entire warranted fleet of 250 U.S. and 192 EPG production aircraft, whichever occured first (10:1-3). The actual total flight time, however, only reached around 200,000 hours in four years (28).

What made this the most complex application of RIW was not only the number of warranted units but also the fact that approximately halfway through the warranty period six of the LRUs transitioned to a RIW at the shop replaceable unit (SRU) level (10:4-2). At the LRU level, the entire defective LRU assembly is sent back to the contractor for repair. At the SRU level, organic Air Force maintenance fault-isolates down to the SRU level using Avionics Intermediate Shop (AIS) test equipment, and then only the defective SRU is returned to the contractor (10:4-2). The radar antenna started the warranty period at the SRU level, while the two LRUs covered by the MTBF guarantee remained at the LRU level throughout the period (10:4-2). The RIW contract specified the conversion to the SRU level would be completed by July 1980. Due to shortages of AIS test equipment, technical orders, and SRU spares, the actual conversion was not completed until January 1981, however (28).

Interim Evaluation. In 1979, the F-16 Program Office contracted with ARINC Research Corporation to evaluate the effectiveness of the F-16 RIW program (28). The evaluation was conducted about halfway through the warranty period, with only 16 percent of the projected total program flying hours flown (29:ix). The following is the summary of that evaluation:

> Based on an interim evaluation, ARINC Research concludes that the F-16 RIW program has been beneficial to date. The government and all the contractors will most likely benefit financially from the program. Reliability levels of both warranted and nonwarranted equipments are acceptable in terms of original program office expectations; no outstanding reliability gains were observed for the warranted equipment (29:ix).

Research Objective

The objective of this study was to determine if the Air Force application of RIW in the past has been effective; has the warranty achieved the higher reliability and reduced cost potential the Air Force paid for? Was the warranted equipment significantly more reliable than it would have been without the warranty? In order to accomplish this, the F-16 RIW program, which has been the most comprehensive application of RIW to date, was investigated. ARINC recommended in its interim evaluation that a follow-on report be prepared to more precisely define the economics and reliability experience upon completion of the F-16 RIW program. This research would, in part, do just that, by evaluating the reliability growth exhibited by the nine warranted LRUs during the entire warranty period.

Research Questions

1. As compared with the reliabilities (MTBFs) of nine functionally similar non-warranted LRUs in the F-15, are the reliabilities (MTBFs) of the nine F-16 warranted LRUs significantly higher?

2. As compared with functionally similar non-warranted LRUs in both the F-15 and F-16, did the nine F-16 warranted LRUs exhibit a significantly higher reliability growth during the first four years of operation?

II. Methodology

Overview

Chapter I provided a background of and the justification for the research on the effectiveness of the F-16 reliability improvement warranty program. The basic problem and the formulated research questions were defined. This chapter describes in detail the specific procedures employed in the research design, including both data acquisition and data analysis. Definitions of key terms, as they relate to this study, are presented first. Then, a detailed discussion of the data used for the study, followed by the methodology devised to answer each of the research questions is presented. Finally, the assumptions and the limitations of the research method are summarized.

As stated in Chapter I, the F-16 Program Office contracted with the ARINC Research Corporation to evaluate the effectiveness of the F-16 RIW at the halfway point of the warranty period. The research questions posed by this study were answered by analyzing available data for the entire four year warranty period, using, for the most part, the same concepts and procedures used by ARINC in their interim evaluation. This study was designed to analyze the effects of a RIW on the reliability of a system. Specifically, does a warranted system have a significantly greater mean time between failure than a functionally similiar non-warranted system?

To determine whether a RIW does influence the reliability of the warranted equipment, this research first compared the field reliabilities of the nine warranted F-16 LRUs with those of functionally similar non-warranted F-15 LRUs. Then the growths in reliability, over a four year period, of the F-15 LRUs plus nine non-warranted F-16 LRUs were compared with the reliability growths exhibited by the nine warranted F-16 LRUs. Specifically, this analysis was designed to detect whether the contractors made substantial efforts to improve equipment reliability during early production.

Key Terms Defined

The following key terms are defined as they apply to this study. While most have relatively common connotations, they must be refined to reflect their exact applications in this study.

Reliability is "the probability that an item can perform its intended function for a specified interval under stated conditions" (30:8).

Reliability Growth is "the positive improvement of the reliability of equipment through the systematic and permanent removal of failure mechanisms" (21:3). It requires a conscious engineering effort to attain higher levels of reliability through the elimination of design weaknesses.

Failure is an "event in which a previously acceptable item does not perform one of more of its required functions within the specified limits under specified conditions" (21:3). An item which is found to be broken or damaged which would "cause failure under operational conditions" is also a failure (21:3).

Mean Time Between Failures (MTBF) is the average time interval between failures, measured in hours. It is considered to be a primary measure of reliability for repairable items. For the purpose of this research design, Mean Flight Hours Between Failures (MFHBF) will be used exclusively. MFHBF is equal to the total flying time of the equipment for a specified time interval divided by the number of relevant failures during that interval.

Line Replaceable Unit (LRU) is "the first level of disassembly below the system level that would be carried as a line item of supply at base level" (10:3-4). It is a "black box" item which is usually removed from the aircraft and replaced as a single unit.

Shop Replaceable Unit (SRU) is a component of a LRU that has a unique stock number and is maintained by base level supply to support LRU intermediate level repair (31:627). In contrast to the LRU, which is removed and replaced on the flightline, SRUs require disassembly of the LRU in the shop. A circuit board assembly is an example of a SRU.

Work Unit Code (WUC) is a unique identifying code assigned to LRUs, SRUs, and other components. It is a combination of five alpha-numeric characters. "The first two characters identify the system, the next two, the subsystem, and the fifth, the component" (31:748). Codes are listed in the appropriate weapon system WUC Manual, i.e. T.O. 1F-16A-06.

Data Collection

Maintenance Data Collection System. The Air Force Maintenance Data Collection System (MDCS), as directed by Air Force Manual 66-1, is designed to provide useful maintenance data to all management levels within the Air Force. MDCS was the only data source common to both the F-16 and F-15 aircraft for the time periods involved in the study. While the contractually required semiannual RIW data reports contained extensive failure data on the nine warranted F-16 LRUs, there was no similar data source for the non-warranted F-15 LRUs. So MDCS, or more specifically, the D056 system was thus the source for the data used in this analysis. The specific report used was the LOG-LOE(AR)7170 report (LOG-MMO(AR)7170 prior to 1981), which was formerly called the "6-LOG report". It is entitled "Maintenance Actions, Man-Hours, and Aborts by Work Unit Code" (32:1). The data, on microfiche cataloged B5006, were obtained from the archives of the Historical Section, Headquarters, Air Force Logistics Command, Wright-Patterson AFB, OH.

The data of interest included total fleet flying hours per month and the total number of failures by WUC per month. The B5006 catalog contained separate reports for each of the two models of the F-16 (A and B) covered by the warranty. The failure data from each report was thus combined for this study. The catalog contained only one report for the F-15, already containing a compilation of data for both the F-15A and F-15B. The failure samples for this study consisted of 48 monthly observations for each aircraft - from January 1975 to December 1978 for the F-15 and from January 1979 to December 1982 for the F-16. This latter time period was the actual warranty period for the F-16 RIW. The time interval selected for the F-15 corresponded to the similar life cycle phase as that of the F-16 warranty period. The selected time periods start just after the initiation of production for each aircraft. The F-15 became operational, with the delivery of the first aircraft to the Tactical Air Command (TAC) in November 1974; the first F-16 was delivered to TAC in January 1979 (33:399,447).

Shortcomings of AFM 66-1 Data. The Air Force MDCS has often been maligned as an inaccurate and incomplete source of maintenance data. In fact, in 1983, "the GAO issued a report on the inadequacy, inaccuracy, and inefficiency of the USAF's DO56/66-1 maintenance data collection system" (34:197). One problem with the system is that it does not allow for the direct comparison of contractually specified MTBFs. Only

MFHBFs are tracked, not MTBFs. The calculation of an MTBF requires that total operation times, both ground and flight, be known; the MDCS only tracks flight times. The system does provide an indication of reliability levels and trends, however. Since this study was not concerned with the actual, absolute reliability levels and reliability growths of each of the aircraft but with the relative differences between them, this problem was considered irrelevant. It was assumed for this study that the ratio of ground operating time to flight time was the same for both aircraft.

Another problem often mentioned about the MDCS is that maintenance failure data is reported the month it is received and not the month the failure actually occurred, while flight time is reported the month it is recorded (35:IIE-62). For this study, it was assumed that the lag in the reporting of failure data was the same for both aircraft. This assumption plus the fact that this analysis covered relatively long periods of time makes this second problem with the MDCS also insignificant.

A third often-cited shortcoming of the MDCS is inaccurate data (34:197; 35:IIE-54). It was not unreasonable to assume for this study that since both sets of failure data came from the same data collection system, the F-15 data was no more or no less accurate than the F-16 data.

The last shortcoming considered for this study was the fact that the MDCS includes many failures which would not be counted as failures in formal reliability demonstration testing (35:IIE-58; 36:466). Examples include accidental damage, tire wearout, and minor adjustments (36:466). Again, there was nothing to indicate that this shortcoming would have a different impact on the collection of F-15 versus F-16 data. The percentage of "insignificant failures" recorded by the MDCS was assumed to be the same for both the F-15 and F-16.

MDCS Failure Definition. A failure was defined in general terms earlier in this chapter. The MDCS computer logic for determining failures is not that simple, however. The MDCS defines failure in terms of How Malfunctioned (How Mal) codes and action taken codes. The How Mal code "consists of three characters and is used to identify the nature of the equipment defect, or the status of the action being accomplished" (37:12). These codes are standard throughout the Air Force. The action taken code consists of one character and is used to identify what specific work was done on the equipment (37:11). Failures are tracked and reported by individual WUCs.

In general, the MDCS counts an item as a failure if maintenance actions take place, or if the item is removed and confirmed defective. Specifically, the MDCS computer definition of a failure consists of the following two decision rules (32:5):

1. Any Type 1 How Mal code in combination with an action taken code of F, K, L, or Z.

2. Any Type 1 How Mal code in conjunction with an action taken code of P or R, provided the removed item was not found serviceable (action taken code B) at the bench check station.

A Type 1 How Mal code indicates the "item no longer meets the minimum specified performance requirement due to its own internal failure pattern" (38:18). An overwhelming majority of How Mal codes are designated Type 1 (37:46). The action taken codes listed above are defined briefly as follows (37:11,12):

F - Repair
K - Calibrated - Adjustment Required
L - Adjust
Z - Corrosion Repair
P - Removed
R - Removed and Replaced
B - Bench Checked Serviceable

The MDCS computer logic definition of failure was changed in March 1981 (35:IIE-62,76). The change affected the definition of failure at the two and three position WUC level (35:IIE-76,77,79). But since all LRUs selected for this study were at the four position WUC level (i.e., 7 4 A A O), it was assumed that this logic change had no real impact on the study.

Research Design for Research Question One

Overview. To review, the first research question was - As compared with the reliabilities of nine functionally similar non-warranted LRUs in the F-15, are the reliabilities of the nine F-16 warranted LRUs significantly higher? The research approach used to answer this question compared the observed reliabilities (as measured by MFHBF) of the nine warranted F-16 LRUs with the observed reliabilities (MFHBFs) of functionally similar F-15 LRUs.

The following is a brief summary of the steps required to answer research question one:

1. Identify the non-warranted F-15 LRUs that perform similar functions as the warranted F-16 LRUS.

2. Calculate MFHBFs for the selected non-warranted LRUs using DO56 data.

3. Calculate MFHBFs for the nine warranted LRUs using DO56 data.

4. Perform a statistical F test to determine whether the MFHBFs for each of the nine F-16 warranted LRUs are significantly higher than those of the F-15 LRUs.

For the basis of comparison, the third year of production MFHBFs were calculated and compared for each aircraft. For the F-16, this was January to December 1981, and for the F-15, January to December 1977. The third year was selected for comparison because it was assumed for this study that any reliability improvement in the F-16, as a direct result of the RIW, would have already been incorporated by the third year.

Identificaton of LRUs for Comparison. Ten LRUs in the F-15 with similar functions as the nine F-16 warranted LRUs were selected for this study. They were the same items of

TABLE I

F-16 WARRANTED LINE REPLACEABLE UNITS

WUC	F-16 LRU Description	Manufacturer
14AAO	Flight Control Computer	Lear-Siegler, Inc.
74AAO	Radar Antenna	Westinghouse
74ABO	Radar Low Power Receiver	Westinghouse
74ACO	Radar Transmitter	Westinghouse
74ADO	Radar Signal Processor	Westinghouse
74AFO	Radar Computer	Westinghouse
74BAO	Head-Up (HUD) Pilot Display	Marconi Avionics
74BCO	HUD Electronic Unit	Marconi Avionics
74DAO	Inertial Navigation Unit (INU)	Singer-Kearfott

Source: (10:4-1; 39)

equipment included in the ARINC interim evaluation (29:2-7). Tables I and II list the warranted F-16 and the selected F-15 LRUs by work unit code and LRU description. Note that the F-15 flight control computer is a combination of two separate LRUs. The descriptions listed came from the work unit code manuals for each aircraft. The F-15 and F-16 have only one of each of the respective 19 LRUs on board.

MFHBF Calculations. When comparing the two similar LRUs, one from the F-16 and one from the F-15, one must account for differences in design specifications, operational and maintenance environments, and other related factors which may affect the reliability data. It was reasonable to assume

TABLE II

EQUIVALENT F-15 LINE REPLACEABLE UNITS

F-15 WUC	F-15 LRU Description	F-16 WUC
52AAO and 52ABO	Flight Control Computer	14AAO
74FUO	Radar Antenna	74AAO
74FCO	Radar Receiver	74ABO
74FAO	Radar Transmitter	74ACO
74FFO	Radar Target Processor	74ADO
74FQO	Radar Data Processor	74AFO
74KAO	Head-Up (HUD) Pilot Display	74BAO
74KCO	HUD Signal Data Processor	74BCO
71AEO	Inertial Measurement Unit (IMU)	74DAO

Source: (40)

for this study that the operational and maintenance environments of the two aircraft were very similar. While the operational roles of the aircraft are somewhat different, there was no reason to believe this difference was a cause for concern for this analysis. The possible significant factor that must be addressed, however, is the design difference between each of the comparable LRUs from each aircraft.

The LRUs in the F-16 and their counterparts in the F-15 are not identical pieces of equipment. They were not made by the same manufacturer and they did not contain the same number of SRUs or electronic components. The comparable LRUs did, however, perform identical functions. This latter point was important to the development of this methodology, since it has been shown that reliability is directly related to a system's function (29:2-5). "It is important, therefore, that only LRUs of similar function be compared for reliability differences that might arise from RIW incentives" (29:2-5).

A normalizing technique developed in the ARINC report was used to account for the differences in system complexity between the comparable F-15 and F-16 LRUs. The technique is based on the fact that the reliability of a system is related to the number of components that make up the system. Ideally, the total number of all the electronic parts in each of the LRUs would be used in this normalization process. However, since that kind of detailed information was not available to the researcher, the total number of SRUs in each LRU was used to calculate a "complexity factor" (29:2-5). The "complexity factor" is defined as the number of SRUs in the F-15 LRU divided by the number of SRUs in the equivalent F-16 LRU (29:2-5). This normalization technique is based on the fact that the failure rate for an entire system is the sum of the individual failure rates of the components that make up the system (41:76; 42:213). The following assumptions also apply for this normalization technique to be valid (29:2-11):

1. The electronic equipment failures are exponentially distributed, and the same "fundamental failure mechanisms

exist in F-15 and F-16 SRUs and in the same proportion."

2. The F-15 SRU contains the same average number of electronic parts as the F-16 SRU.

3. The inherent failure rates of the electronic parts in the F-15 SRU are identical to the failure rates of the same types of parts in the F-16 SRU.

The F-15 and F-16 Work Unit Code Manuals (T.O. 1F-15A-06 and T.O. 1F-16A-06) list all the SRUs or modules that make up each LRU. The only manuals available for this study, however, were current. Since there was a likely chance the LRUs included in the study were modified sometime between now and the focal time periods of this analysis, the current WUC manuals could not be used to determine the number of SRUs per LRU. The ARINC interim report listed the number of SRUs for each of the LRUs included in this analysis; however, no reference was made to the source of their data. Because several substantial differences existed between the numbers reported in the ARINC research and those listed in the current WUC manuals, the following method was devised to determine how many SRUs made up each of the 19 LRUs. The DO56 - B5006 report lists all the WUCs on file in the master record, with SRUs listed under the parent LRU (32:1). The total number of different SRUs listed for each of the ten F-15 LRUs during 1976 and 1977 and for each of the nine F-16 LRUs during 1980 and 1981 was used to calculate the "complexity factor."

Under the assumption that LRU failures are exponentially distributed, the calculation of the mean life or MFHBF is quite straightforward. The maximum likelihood estimator, $\hat{\theta}$, of the mean life parameter θ (MFHBF) is described by

$$\hat{\theta} = T / r \tag{1}$$

where T is the total accummulated flight time over a specified time interval and r is the total number of failures observed during the interval (42:250,251). The MFHBFs for both F-15 and F-16 LRUs were calculated using the above formula. The F-15 MFHBFs for each LRU were then normalized by multiplying this figure by the "complexity factor" (the number of F-15 SRUs divided by the number of F-16 SRUs) (29:2-11). This normalized F-15 MFHBF was then compared with the MFHBF for the equivalent F-16 LRU.

Statistical Comparison. A statistical F test was used to compare each of the nine F-16 LRU MFHBFs with those of the equivalent F-15 LRUs. The test determined whether the F-16 MFHBFs were significantly greater than those of the F-15. The hypothesis in this case was directional, and a one-tailed statistical test was required (43:353).

The alternate hypothesis (H_a) was that the F-16 LRU MFHBF is statistically greater than the equivalent normalized F-15 LRU MFHBF:

$$H_a: \theta_{16} > \theta_{15}$$

The associated null hypothesis (H_0) was that there is no discernible difference between the F-16 and F-15 LRU MFHBFs:

$$H_0: \theta_{16} = \theta_{15}$$

The decision rule for conducting the test was based on a five percent (.05) level of significance.

The development of the F test statistic was based on the fact that for the exponential distribution the quantity $2r\hat{\theta}/\theta$ is chi-square (X^2) distributed with 2r degrees of freedom (42:267). It was also based on the fact that the ratio of two independent chi-square random variables (X_1 and X_2) defines the following F distribution (44:70):

$$F = \gamma_2 X_1 \;/\; \gamma_1 X_2 \tag{2}$$

where X_1 has γ_1 degrees of freedom and X_2 has γ_2 degrees of freedom. By substituting $2r_1\hat{\theta}_1/\theta_1$ for X_1, $2r_2\hat{\theta}_2/\theta_2$ for X_2, $2r_1$ for γ_1, and $2r_2$ for γ_2 in Eq (2) the following results after simplification:

$$F = \hat{\theta}_1 \theta_2 \;/\; \hat{\theta}_2 \theta_1 \tag{3}$$

Since the null hypothesis equates θ_1 and θ_2, Eq (3) reduces to

$$F = \hat{\theta}_1 \;/\; \hat{\theta}_2 \tag{4}$$

which is an F distribution with $2r_1$, $2r_2$ degrees of freedom.

The test statistic in this specific case was thus

$$F_c = \hat{\theta}_{16} / \hat{\theta}_{15} = \text{F-16 MFHBF} / \text{F-15 Normalized MFHBF} \quad (5)$$

The rejection decision criteria was the following: if the calculated value of F (F_c) is greater than the critical value of F, reject the null hypothesis in favor of the alternate hypothesis at a .05 significance level (43:353). The critical value of F (from tables of the percentage points of the F distribution) was based on $2(r_{16}-1)$, $2(r_{15}-1)$ degrees of freedom rather than $2r_{16}$ and $2r_{15}$ because one parameter ($\hat{\theta}$) had been calculated from the r failure variables (19:52). The rejection of the null hypothesis would answer the first research question in the affirmative.

A corollary hypothesis test was used to determine whether the F-15 MFHBF was significantly greater than the MFHBF of the F-16 in those cases where the null hypothesis in the above test could not be rejected. The corollary alternate hypothesis was thus

$$H_a: \quad \theta_{16} < \theta_{15}$$

The null hypothesis was identical to that above; that there is no difference between the F-16 and F-15 LRU MFHBFs:

$$H_o: \quad \theta_{16} = \theta_{15}$$

The decision rule for conducting this corollary test was also based on a five percent (.05) level of significance. The test statistic was $F_c = \hat{\theta}_{15} / \hat{\theta}_{16}$. Again, the rejection decision criteria was the following: if F_c is greater than the critical value of F, from the F tables, then reject the null hypothesis in favor of the alternate hypothesis at a .05 significance level. The critical value of F was based on $2(r_{15}-1)$, $2(r_{16}-1)$ degrees of freedom.

Confidence Intervals. Confidence intervals provide a measure of the uncertainty regarding the MFHBF estimates. Kapur and Lamberson have shown that for reliability studies where only the number of failures over a time interval have been recorded, the following $100(1-\alpha)\%$ two-sided confidence interval applies (42:254):

$$2T / \chi^2_{\alpha/2,\ 2(r+1)} \leq \theta \leq 2T / \chi^2_{1-\alpha/2,\ 2r} \tag{6}$$

where T equals the interval of time and r equals the number of observed failures over that time interval and the two denominators represent the chi-square table values with the appropriate significance levels and degrees of freedom. For this study 90% confidence intervals for the F-15 and F-16 LRUs were calculated using Eq (6). Normalized intervals were calculated for the F-15 by multiplying T by the "complexity factor" discussed above, before using Eq (6).

Research Design for Research Question Two

Overview. To review, the second research question was - As compared with functionally similar non-warranted LRUs in both the F-15 and F-16, did the nine F-16 warranted LRUs exhibit a significantly higher reliability growth during the first four years of operation? The research approach used to answer the second question compared the reliability (MFHBF) growths of the nine warranted F-16 LRUs with the MFHBF growths of the ten non-warranted F-15 LRUs and also with the combined MFHBF growth of nine dissimilar non-warranted F-16 LRUs, over an equivalent four year period.

The following briefly describes the steps developed to answer research question two:

1. Identify nine non-warranted electronic F-16 LRUs that are similar in complexity to the warranted LRUs.

2. Calculate the reliability growth parameters for each of the F-15 and the warranted F-16 LRUs, using the Army Materiel Systems Analysis Activity (AMSAA) Reliability Growth Model as a basis.

3. Calculate the reliability growth parameters for both a combined total of the warranted F-16 LRUs and a combined total of the non-warranted F-16 LRUs.

4. Perform a statistical F test using the growth parameters to determine whether the reliability growths exhibited by the warranted F-16 LRUs are significantly higher than those exhibited by non-warranted LRUs in both the F-15 and F-16.

Equivalent four year time intervals were selected for both aircraft as a basis for the reliability growth comparison. For the F-16, the interval corresponded to the actual warranty period, January 1979 to December 1982. For the F-15, the equivalent period was January 1975 to December 1978. Research has shown that reliability improvements which are a direct result of a RIW rarely occur after the two year point of the warranty (17:98). Despite this, the entire four year warranty period and the equivalent F-15 time period were selected because the effects of the improvements in terms of MFHBF growth are often not observed "until the percentage of improved equipment becomes a substantial part of the entire population"; which may take several years (36:466).

In addition to the F-16 and F-15 LRUs identified for research question one, nine other non-warranted F-16 LRUs were selected for the second part of this analysis. For the most part, the LRUs selected were similar in complexity to the warranted LRUs, and most were items of electronic avionics equipment. Table III lists these non-warranted F-16 LRUs. The first three LRUs listed were the three that were dropped from the original 12 LRUs considered for the F-16 RIW (45:223). The LRU descriptions are those listed in the F-16 WUC Manual. Again, these nine LRUs were also included in the ARINC interim evaluation (29:2-7).

Reliability Growth Modeling. The choice of how to analyze reliability growth data is probably best made after the data has been collected and studied. In reality, the data analysis, or more specifically, the reliability growth modeling, may be more an art than a science. For, "no model can

TABLE III

F-16 NON-WARRANTED LRUs INCLUDED IN THE STUDY

WUC	LRU Description
74CAO	Fire Control Computer
74EAO	Radar Electro-Optical Display
74EB0	Radar Electro-Optical Electronics
14ADO	Flight Control Panel
14FBO	Air Data Electronic Components
74DDO	Fire Control Nav. Panel
75DAO	Stores Control Panel
75DBO	Missile Remote Interface Unit
75DCO	Stores Mgt. Central Interface Unit

Source: (39)

completely characterize the reliability evolution of a complex system design" (46:43). The underlying basis for reliability growth modeling is the fact that successive times between failures will tend to increase in the presence of improving reliability (47:113). Numerous models have been developed to represent the reliability growth of a wide variety of systems. In fact, Military Handbook 189 (MIL-HDBK-189), entitled Reliability Growth Management, describes 17 different models (47). Of these 17, the two most commonly used are the Duane Model and the Army Materiel Systems Analysis Activity (AMSAA) Model (22:122). MIL-HDBK-189 suggests the Duane Model is best used during planning phases, while the AMSAA Model is best used for assessment and tracking (22:122). The Duane Model's advantage stems from its mathematical simplicity; while the advantages of the AMSAA Model are its versatility and its associated statistical properties (22:122). The AMSAA Model "has found wide acceptance, especially among the military and military contractors" (48:20), and is the model recommended by MIL-HDBK-189 because it is "the most versatile for tracking growth" (22:43). Because of this and the fact that the ARINC interim study demonstrated the usefulness of the model in assessing the reliability growths of F-15 and F-16 LRUs, the AMSAA Model was used to evaluate the LRU reliability growths in this analysis.

AMSAA Reliability Growth Model. Before discussing the AMSAA Model, a brief explanation of the Duane Model is required, since the Duane postulate really led to the development of the AMSAA Model (22:54).

In 1962, J. T. Duane, of the General Electric Company, developed probably the most popular model of reliability growth (48:11; 49:390). He postulated that an approximate linear relationship existed between the logarithm of the cumulative failure rate (or cumulative MTBF) and the logarithm of the cumulative operating time (22:47). In other words, the plot of cumulative failure rate against cumulative time would approximate a straight line on log-log paper. The cumulative failure rate is defined as the cumulative number of failures divided by the cumulative test time, and is the inverse of the cumulative MTBF for system failures following an exponential distribution. Equation (7) expresses the above relationship mathematically:

$$\ln \lambda_c(t) = \ln K - \alpha \ln t \tag{7}$$

Through simplification, Duane's Growth Model is represented in the following form (46:9,10; 48:12,13):

$$\lambda_c(t) = Kt^{-\alpha} \tag{8}$$

where

$\lambda_c(t)$ = the cumulative failure rate

t = the cumulative test time

K = the cumulative failure rate at $t = 0$, a constant

α = the Duane growth rate constant, the negative of the slope of the growth curve

Although the two parameters, K and α, can be estimated using standard curve fitting methods, such as the least squares method, the Duane Model is probably more useful when applied as a graphical technique (46:10; 48:13). When plotted on log-log paper, K is estimated by the intercept of the line and α is estimated by the line's slope (48:14). The AMSAA Model, while somewhat more complicated than the Duane Model, enables one to go a step further by calculating maximum likelihood estimators of its parameters.

The AMSAA Model was developed by Larry H. Crow, a researcher working for the U.S. Army Materiel Systems Analysis Agency. Crow used the Duane postulate (the plot of the logarithm of the cumulative failure rate versus the logarithm of the cumulative time is linear) in the empirical development of his model (22:54). Crow has shown that the Dua.. growth model is mathematically equivalent to a Weibull process where failure times are assumed to occur according to a nonhomogeneous Poisson process with the following Weibull intensity function (50:438,439):

$$r(t) = \lambda\beta t^{\beta-1}, \text{ where } \lambda, \beta > 0 \qquad (9)$$

where λ, the scale parameter, equals $e^{\ln K}$ (where ln K is from Eq (7)), and β is the shape or growth parameter and is related to the slope of the growth curve (22:55). As such, β reflects the rate at which reliability (MFHBF) increases or decreases (50:439). The Weibull process growth parameter, β, is related to the Duane Model by the following: $\beta = 1 + \alpha$, where α is the Duane growth rate constant from Eq (8) (22:57). Because α is the negative of the slope, the slope of the cumulative failure rate versus cumulative time curve plotted on log-log paper is given by $1 - \beta$. When β is less than one, the failure rate, r(t), is decreasing, indicating reliability growth; when β is greater than one, r(t) is increasing, implying some form of system reliability deterioration (47:127; 51:385).

The AMSAA Model uses a nonhomogeneous Poisson process (NHPP), which is often termed a "Weibull Process," to model reliability growth (52:426). It is important to note that this does not imply the use of the Weibull distribution. "Therefore, statistical procedures for the Weibull distribution do not apply" to the AMSAA Model (47:127). Very briefly, the difference between an NHPP and a homogeneous Poisson process (HPP) is that the failure rate varies with time for the NHPP and is constant for a HPP (52:428).

Growth Parameter Calculations. The use of the AMSAA Model permits the estimation of the model parameters by statistical means. The method of maximum likelihood provides estimates of both the shape parameter, β, and the scale parameter, λ (47:139). Since individual failure times were not available through the MDCS D056 system, and only the flying times and the number of failures per month were obtainable, the procedures outlined in MIL-HDBK-189 for grouped data were used for this analysis. Using these procedures, the estimation of β and λ is possible through maximum likelihood methods.

Parameter estimation from grouped data is based on the assumption that there are k intervals of time which are defined by the boundaries $t_0, t_1, t_2, \ldots, t_k$, where $t_0 = 0$ (29:A-3). The time intervals do not necessarily have to be equal in length (47:139). The number of failures observed in the interval from t_{i-1} to t_i is denoted by N_i. The following equation from MIL-HDBK-189 was used to calculate $\hat{\beta}$, the maximum likelihood estimate of β:

$$\sum_{i=1}^{k} N_i \left[\frac{t_i^{\hat{\beta}} \ln t_i - t_{i-1}^{\hat{\beta}} \ln t_{i-1}}{t_i^{\hat{\beta}} - t_{i-1}^{\hat{\beta}}} - \ln t_k \right] = 0 \qquad (10)$$

where $t_0 \ln t_0$ is defined as zero (47:139). This non-linear equation can be solved by any number of numerical analysis iterative procedures. For this study, the secant method was used. The general iteration formula for this method is

$$x_{n+1} = x_n - f(x_n) \left[\frac{x_n - x_{n-1}}{f(x_n) - f(x_{n-1})} \right] \qquad (11)$$

where $n \geq 1$ (53:80). For this study, the researcher developed a Hewlett-Packard 41C calculator program, using Eqs (10) and (11), to calculate $\hat{\beta}$ to four decimal places. The growth parameter of the F-15 LRU was then compared with that of the equivalent F-16 LRU to determine whether there was a statistical difference between the two.

Statistical Comparison. Again, a statistical F test was used to compare the growth parameters, $\hat{\beta}$, of the F-15 and the F-16 LRUs and the warranted and non-warranted F-16 LRUs. Like the hypothesis in research question one, this hypothesis was also directional, so a one-tailed statistical test was required.

Since the slope of the cumulative failure rate versus cumulative time curve plotted on log-log paper is equal to $1 - \beta$, the smaller β is, the greater the slope is. And the greater the slope of the line is, in an absolute sense, the greater is the reliability growth experienced by the system. Thus, the LRU experiencing the greater reliability growth is the one with the smaller growth parameter, β. Since only the differences in the growth parameters were of interest to answer research question two, there was no need to normalize the F-15 LRUs to a common complexity level.

F-15 Versus F-16. The alternate hypothesis for the first part of this comparison was that the warranted F-16 LRU reliability growth was statistically greater than the equivalent F-15 LRU reliability growth.

$$H_a: \quad \beta_{16} < \beta_{15}$$

The associated null hypothesis was that there was no discernible difference between the reliability growths of the warranted F-16 and non-warranted F-15 LRUs.

$$H_o: \quad \beta_{16} = \beta_{15}$$

The test was based on a five percent (.05) level of significance. To test whether the growth parameters were the same, the following test statistic, developed by Crow, was used (51:398):

$$F_c = \hat{\beta}_{15} / \hat{\beta}_{16} \tag{12}$$

which is based on $2N_{15}$, $2N_{16}$ degrees of freedom, where N is the total number of failures over four years for the respective LRU (29:A-6; 51:398). The rejection decision criteria was the following: if the calculated value of F (F_c) is greater than the critical value of F, reject the null hypothesis in favor of the alternate hypothesis at a .05 significance level (43:353). The critical value of F, from the F tables, was based on $2N_{15}$, $2N_{16}$ degrees of freedom. The rejection of the null hypothesis would, in part, answer the second research question in the affirmative.

As in the methodology for the first research question, in those cases where the null hypothesis in the above test could not be rejected, a corollary hypothesis test was used to determine whether the F-15 reliability growth was significantly greater than that of the F-16. The corollary alternate hypothesis was thus

$$H_a: \ \beta_{15} < \beta_{16}$$

The null hypothesis was identical to that above; that there is no difference between the F-16 and F-15 LRU MFHBF growth.

$$H_o: \ \beta_{15} = \beta_{16}$$

The decision rule for conducting this corollary test was also based on a five percent level of significance. The test statistic was $F_c = \hat{\beta}_{16} / \hat{\beta}_{15}$. Again, the rejection decision criteria was the following: if F_c is greater than the critical value of F, then reject the null hypothesis in favor of the alternate hypothesis at a .05 significance level. The critical value of F was based on $2N_{16}$, $2N_{15}$ degrees of freedom.

F-16 RIW Versus F-16 Non-RIW. The alternate hypothesis for the second part of the comparison was that the reliability growth of the combination of the entire group of warranted F-16 LRUs (the RIW "system") was statistically greater than that of the combination of the entire group of non-warranted F-16 LRUs (the Non-RIW "system"):

$$H_a: \quad \beta_{RIW} < \beta_{NONRIW}$$

The associated null hypothesis for this second part was that there was no discernible difference between the reliability growth of the RIW "system" and that of the Non-RIW "system":

$$H_o: \quad \beta_{RIW} = \beta_{NONRIW}$$

The decision rule for conducting the hypothesis tests was based on a five percent (.05) level of significance.

For this second comparison, the failures of all the RIW LRUs were totaled for each month, and the growth parameter of this group as a whole was calculated using Eq (10). The same applied for the group of non-warranted F-16 LRUs. The idea was to neutralize "any technological differences that might be thought to exist between F-16 and F-15 aircraft" (29:2-18).

The F statistic used to test whether the growth parameters were the same was $F_c = \beta_{NONRIW} / \beta_{RIW}$ (51:398), which is based on $2N_{NONRIW}$, $2N_{RIW}$ degrees of freedom, where N is the total observed number of failures for the respective group (29:A-6; 51:398). Again, the rejection decision criteria was the following: if the calculated value of F (F_c) is greater than the critical value of F, reject the null hypothesis in favor of the alternate hypothesis at a .05 significance level. The critical value of F (from tables of the percentage points of the F distribution) was based on $2N_{NONRIW}$, $2N_{RIW}$ degrees of freedom. The rejection of the null hypothesis, in conjunction with the rejection of the null hypothesis of part one of this comparison, would answer the second research question in the affirmative.

Research Assumptions and Limitations

For the purposes of this analysis, the researcher made several assumptions and also identified certain limitations which had impacts on the analysis. The assumptions were categorized as being either general or statistical in nature. The assumptions and limitations were necessary for research consistency, and are explained below.

Assumptions. The following list reflects the general assumptions applicable to this methodology:

1. Mean Flight Hours Between Failures data was a valid measure of system reliability.

2. The AFM 66-1 Maintenance Data Collection System accurately measured the actual failures and flying time for the selected LRUs.

3. The failure of any one of the LRUs had no effect on the operation of the other LRUs in the study.

4. The differences in the operational environments and the maintenance levels of the F-15 and F-16 were insignificant.

The statistical assumptions applicable to this analysis are the following:

1. The reliability of the equipment included in the study followed the exponential law; failures were chance failures and were distributed exponentially.

2. LRU failures were independent of each other.

3. The use of the system "complexity factor" was a valid means of normalizing the F-15 data.

4. The AMSAA Reliability Growth Model adequately represented the reliability growth of the LRUs included in the study.

Limitations. To adequately research all the areas related to the effectiveness of the F-16 reliability improvement warranty was clearly impossible given the time constraints. The research design only allowed the researcher to make inferences about the reliability and reliability growth of the F-16 LRUs included in the RIW. Other measures of effectiveness, especially cost factors, were not addressed.

No attempt was made to analyze the reliability performance of the European Participating Governments' aircraft included in the F-16 RIW.

III. Analysis of Results

This chapter details the results of the statistical analyses of the two research questions using the methodology described in Chapter II. The appropriate F test statistics were calculated using the data collected from the Air Force MDCS; then these values were compared to the critical F values to determine the acceptance or rejection of the null hypotheses. To provide consistency in the review of the statistical results, each of the hypotheses for each research question is discussed individually.

As discussed in the previous chapter, the source of the data for this analysis was the D056 system of the AFM 66-1 MDCS. The B5006 catalog contained the specific F-15 and F-16 reports required for the study. The F-15 and F-16 reports were filed according to the air logistics center (ALC) responsible for the aircraft. In this case, the F-15 reports were filed under the Warner Robins ALC and those for the F-16 were filed under the Ogden ALC. Failure and flight time data were extracted from these reports and are summarized in Appendix A.

First Research Question

To review, the first research question was - As compared with the reliabilities of nine functionally similar non-warranted LRUs in the F-15, are the reliabilities of the nine

F-16 warranted LRUs significantly higher?

To answer research question one, the observed MFHBF of each of the nine warranted F-16 LRUs was compared to that of its equivalent F-15 LRU(s). The MFHBFs for the F-16 LRUs were calculated, using the total failure and total flight time data for 1981. The F-15 LRU MFHBFs were calculated using the data for 1977. Normalized F-15 MFHBFs were then calculated by multiplying the raw F-15 MFHBFs by the appropriate "complexity factor." These "complexity factors", the ratios of the number of F-15 SRUs per LRU to the number of F-16 SRUs per equivalent LRU, are listed in Table IV. This number of SRUs per LRU or SRU count was derived from the DO56 - B5006 reports. Table V lists the results of the MFHBF calculations for the nine LRU comparisons. Both raw and normalized F-15 MFHBFs are listed.

A statistical F test was used to determine whether the F-16 LRU MFHBFs were significantly greater than those of the equivalent F-15 LRU's, at the five percent significance or alpha level. The null hypothesis stated that there was no discernible difference and the alternate hypothesis stated that the F-16 LRU MFHBF was greater than the equivalent F-15 LRU MFHBF:

$$H_o: \quad \theta_{16} = \theta_{15}$$

$$H_a: \quad \theta_{16} > \theta_{15}$$

TABLE IV

NUMBER OF SRUs PER LRU

LRU Description	F-16 WUC	F-16 SRU Count	F-15 WUC	F-15 SRU Count	C.F.
Flight Control Computer	14AAO	11	52AAO 52ABO	22	2.00
Radar Antenna	74AAO	6	74FUO	10	1.67
Radar Receiver	74ABO	11	74FCO	6	.55
Radar Transmitter	74ACO	8	74FAO	14	1.75
Radar Signal Proc.	74ADO	23	74FFO	25	1.09
Radar Computer	74AFO	13	74FQO	30	2.31
HUD Pilot Display	74BAO	9	74KAO	17	1.89
HUD Electronics	74BCO	13	74KCO	17	1.31
Inertial Nav. Unit	74DAO	14	71AEO	4	.29

C.F. = "Complexity Factor" = F-15 SRU Count / F-16 SRU Count

Source: (54)

The summary of the F test results is given in Table VI. Note that since percentage points of the F distribution tables only list values for degrees of freedom up to 120, an approximation formula was used to calculate the critical F value. Appendix B summarizes the technique used.

The results from Table VI indicated that the null hypothesis of equal MFHBFs can be rejected for six of the nine LRU comparisons. Since the test will lead to an incorrect conclusion only five percent of the time (43:288), it was

TABLE V

OBSERVED MFHBFs OF F-16 RIW LRUs AND EQUIVALENT F-15 LRUs

	F-16 RIW LRUs			F-15 LRUs			
LRU Description	WUC	Number of Failures	MFHBF	WUC	Number of Failures	MFHBF	Norm. MFHBF
Flight Control Computer	14AAO	175	351.0	52AAO 52ABO	125	338.5	677.0
Radar Antenna	74AAO	446	137.7	74FUO	307	137.8	229.7
Radar Receiver	74ABO	375	163.8	74FCO	285	148.5	81.0
Radar Transmitter	74ACO	219	280.4	74FAO	392	107.9	188.8
Radar Signal Proc.	74ADO	157	391.2	74FFO	368	115.0	125.0
Radar Computer	74AFO	156	393.7	74FQO	423	100.0	230.8
HUD Pilot Display	74BAO	181	339.3	74KAO	249	169.9	320.9
HUD Electronics	74BCO	80	767.7	74KCO	172	246.0	321.7
Inertial Nav. Unit	74DAO	460	133.5	71AEO	427	99.1	28.3

Source: (54)

Note 1: The failures and flight hours were based on the following time periods: F-16 - January to December 1981; F-15 - January to December 1977.
Note 2: The MFHBFs were based on 61,418 flight hours for the F-16 fleet and 42,310 flight hours for the F-15 fleet.

TABLE VI

SUMMARY OF F TEST RESULTS - MFHBF COMPARISON

LRU Description	F_c	$F_{.05}$	Decision
Flight Control Comp.	.52	1.21	test further
Radar Antenna	.60	1.13	test further
Radar Receiver	2.02	1.14	reject
Radar Transmitter	1.49	1.15	reject
Radar Signal Proc.	3.13	1.17	reject
Radar Computer	1.71	1.17	reject
HUD Pilot Display	1.06	1.17	do not reject
HUD Electronics	2.39	1.25	reject
Inertial Nav. Unit	4.72	1.12	reject

concluded that the radar receiver, transmitter, signal processor, and computer along with head-up display electronic unit and the inertial navigation unit, all exhibited significantly greater MFHBFs than their counterparts in the F-15. Since the null hypothesis could not be rejected for the HUD pilot display, it was concluded there was no significant difference between the MFHBFs of these two LRUs.

As discussed in Chapter II, a corollary hypothesis test was planned to compare the MFHBFs of those pairs of LRUs that could not be rejected under the initial hypothesis test. This corollary null hypothesis stated that there was no discernible difference between the MFHBFs and the alternate

TABLE VII

SUMMARY OF F TEST RESULTS - COROLLARY MFHBF COMPARISON

LRU Description	F_c	$F_{.05}$	Decision
Flight Control Comp.	1.93	1.21	reject
Radar Antenna	1.67	1.13	reject

hypothesis stated that the F-16 LRU MFHBF was less than the equivalent F-15 LRU MFHBF:

$$H_o: \theta_{16} = \theta_{15}$$

$$H_a: \theta_{16} < \theta_{15}$$

The summary of the F test results for the corollary hypothesis is given in Table VII. The results indicated that the null hypothesis of equal MFHBFs can be rejected for both of the LRU comparisons. It was thus concluded that the F-15 flight control computer and radar antenna exhibited significantly greater MFHBFs than their warranted counterparts in the F-16.

Ninety percent confidence intervals were calculated, using the equation given in Chapter II, for the warranted F-16 LRU MFHBFs as well as the equivalent normalized F-15 LRU MFHBFs. An inspection of these confidence intervals, listed in Table VIII, yields the same conclusions as the statistical F tests discussed above.

TABLE VIII

F-16 AND NORMALIZED F-15 MFHBF 90% CONFIDENCE INTERVALS (CI)

LRU Description	F-16 MFHBF CI	F-15 NORMALIZED MFHBF CI
Flight Control Comp.	(310, 399)	(583, 789)
Radar Antenna	(127, 149)	(209, 253)
Radar Receiver	(150, 179)	(73, 89)
Radar Transmitter	(251, 315)	(174, 206)
Radar Signal Proc.	(343, 448)	(115, 136)
Radar Computer	(345, 451)	(213, 250)
HUD Pilot Display	(300, 385)	(289, 357)
HUD Electronics	(637, 932)	(283, 366)
Inertial Nav. Unit	(124, 144)	(26, 31)

In summary, then, of the nine warranted F-16 LRUs, six exhibited significantly greater third year MFHBFs and thus, better reliability, than their F-15 counterparts; for two of the warranted LRUs, the reverse was true. And there was no statistical difference between the MFHBFs of the F-16 and F-15 HUD pilot displays. This analysis concluded, as did the ARINC interim evaluation of the F-16 RIW (29:2-12), that the F-16 radar transmitter and HUD electronic unit, the two F-16 LRUs covered by a MTBF guarantee, exhibited significantly greater MFHBFs than their counterparts in the F-15. Two significant differences were noted, however, between the results of this research and that of the ARINC study. The ARINC study concluded that the radar computer and the inertial navigation unit exhibited better reliability in the F-15. However, this research has shown just the opposite, that these two LRUs exhibited significantly better third year reliability in the F-16.

The normalizing process to account for differences in system complexity tended to "favor" the F-15 LRUs, since all but two of the F-15 LRUs had a greater number of SRUs per LRU than those of the F-16. In the two cases where the F-16 had the "advantage", the radar receiver and the inertial navigation unit, the MFHBFs of these two F-16 LRUs were greater than those of their F-15 counterparts even before the F-15 MFHBFs were adjusted by the "complexity factor." While not part of this research design, it was noted that had the F-15 MFHBFs not been normalized, and only the raw MFHBFs compared, the results would have changed very little. Six out of the nine warranted F-16 LRUs would still have shown a significantly greater reliability, while three would have exhibited no difference in reliability. None of the F-15 LRUs would have had a significantly greater MFHBF.

Second Research Question

To review, the second research question was - As compared with functionally similar non-warranted LRUs in both the F-15 and F-16, did the nine F-16 warranted LRUs exhibit a significantly higher reliability growth during the first four years of operation?

The second research question was really comprised of two parts. To answer the first part, the observed reliability growth over a four year period of each of the nine warranted F-16 LRUs was compared to the reliability growth of its equivalent F-15 LRU(s). To answer the second part of the question, the observed reliability growth of the entire F-16 RIW "system" was compared to the growth of the entire F-16 Non-RIW "system", where the monthly MFHBFs of the RIW "system" was based on the total number of failures reported for all the nine warranted LRUs and the monthly MFHBFs of the Non-RIW "system" was based on the total failures of all nine non-warranted F-16 LRUs.

The growth parameter, $\hat{\beta}$, of the AMSAA Reliability Growth Model was calculated for each of the nine F-15 and F-16 LRUs and also for both the F-16 RIW and Non-RIW "systems." The growth parameters, which are measures of reliability growth, were calculated to four decimal places using the methodology described in Chapter II. Monthly failure and flight time data for the entire respective four year time periods were used in the calculation of the growth parameters. Thus, 48 iterations of Eq (10) were required just to get one estimation for a single iteration of the secant formula, Eq (11). And an average of seven iterations of the secant formula were required to converge to obtain an estimate of β to four

TABLE IX

RELIABILITY GROWTH PARAMETERS, $\hat{\beta}$, AND TOTAL FAILURES OF F-16 LRUs AND EQUIVALENT F-15 LRUs

	F-16 LRUs		F-15 LRUs	
LRU Description	Number of Failures	$\hat{\beta}_{16}$	Number of Failures	$\hat{\beta}_{15}$
Flight Control Comp.	609	.8598	383	.8529
Radar Antenna	1207	.7712	1013	.8325
Radar Receiver	1177	.7964	855	.9063
Radar Transmitter	803	.7084	1344	.8553
Radar Signal Proc.	455	.7234	959	.7063
Radar Computer	593	.6229	1250	.7647
HUD Pilot Display	595	.8483	718	.8129
HUD Electronics	338	.8850	534	.6456
Inertial Nav. Unit	1375	.8462	1392	.6857
RIW Combined Total	7152	.7802		
Non-RIW Combined Total	3416	.8487		

Source: (54)

Note: The total failures are based on the following time periods: F-16 - January 1979 to December 1982; F-15 - January 1975 to December 1978.

decimal places. Table IX contains the results of the AMSAA Model growth parameter calculations along with the total number of failures for each of the LRUs for the entire respective four year period. Listed at the bottom of Table IX are the results of the calculations for the comparison of the F-16 RIW versus the Non-RIW "systems."

A statistical F test was used to determine whether the reliability growths, as measured by $\hat{\beta}$, of the warranted F-16 LRUs were significantly greater than the growths of the equivalent F-15 LRUs, at a five percent alpha level. An identical F test was used to determine whether the reliability growth of the RIW "system" was significantly greater than that of the Non-RIW "system." The null hypothesis for the first part of the question stated there was no discernible difference; the alternate hypothesis stated that the reliability growth of the F-16 LRU was greater than that of its F-15 counterpart or in this case the growth parameter, β_{16}, of the F-16 LRU was less than the growth parameter, β_{15}, of the F-15 LRU:

$$H_o: \quad \beta_{16} = \beta_{15}$$
$$H_a: \quad \beta_{16} < \beta_{15}$$

The null hypothesis for the second part of the question also stated there was no difference, while the alternate hypothesis stated that the reliability growth of the RIW "system" was greater than that of the Non-RIW "system":

$$H_o: \quad \beta_{RIW} = \beta_{NONRIW}$$
$$H_a: \quad \beta_{RIW} < \beta_{NONRIW}$$

TABLE X

SUMMARY OF F TEST RESULTS
F-16 RIW LRU VERSUS F-15 LRU RELIABILITY GROWTH COMPARISON

LRU Description	F_c	$F_{.05}$	Decision
Flight Control Comp.	.99	1.11	test further
Radar Antenna	1.08	1.07	reject
Radar Receiver	1.14	1.08	reject
Radar Transmitter	1.21	1.08	reject
Radar Signal Proc.	.98	1.10	test further
Radar Computer	1.23	1.09	reject
HUD Pilot Display	.96	1.10	test further
HUD Electronics	.73	1.12	test further
Inertial Nav. Unit	.81	1.06	test further
RIW vs. Non-RIW system	1.09	1.03	reject

Table X contains the summary of the F test results. Again, the technique explained in Appendix B was used to approximate the critical $F_{.05}$ values listed in Table X.

The F test results indicated that the null hypothesis of equal reliability growths can be rejected in only four out of the nine LRU comparisons. It was therefore concluded that the radar antenna, receiver, transmitter, and computer all exhibited significantly higher reliability growths than their counterpart LRUs in the F-15.

Again, a corollary hypothesis test was used to compare the reliability growths of those pairs of LRUs that could not be rejected under the initial hypothesis test. The purpose of the corollary test was to determine if the observed reliability growths of the F-15 LRUs were, in fact, greater than those of the warranted F-16 LRUs. This second corollary null hypothesis stated that there was no discernible difference and the alternate hypothesis stated that the reliability growth of the F-15 LRU was greater than that of its F-16 counterpart or in this case the growth parameter, β_{15}, of the F-15 LRU was less than the growth parameter, β_{16}, of the warranted F-16 LRU:

$$H_o: \quad \beta_{15} = \beta_{16}$$
$$H_a: \quad \beta_{15} < \beta_{16}$$

Table XI summarizes the results of the F tests for this corollary hypothesis. The results indicated that the null hypothesis can be rejected for two of the five corollary LRU comparisons. It was thus concluded that the F-15 HUD electronic and inertial navigation units exhibited significantly greater reliability growth over the four year period than their warranted F-16 counterparts. Furthermore, for three of the LRUs, the flight control computer, the radar signal processor, and the HUD pilot display, this research concluded there was no statistical difference in the reliability growths between those in the F-15 and those in the F-16.

TABLE XI

SUMMARY OF F TEST RESULTS - F-16 RIW LRU VERSUS F-15 LRU
COROLLARY RELIABILITY GROWTH COMPARISON

LRU Description	F_c	$F_{.05}$	Decision
Flight Control Comp.	1.01	1.11	do not reject
Radar Signal Proc.	1.02	1.10	do not reject
HUD Pilot Display	1.04	1.10	do not reject
HUD Electronics	1.37	1.12	reject
Inertial Nav. Unit	1.23	1.06	reject

The F test results for the second part of research question two indicated that the null hypothesis of equal reliability growths for the RIW and Non-RIW "systems" can be rejected. It was therefore concluded that the "system" of warranted F-16 LRUs as a group exhibited a significantly higher reliability growth than the entire "system" of non-warranted F-16 LRUs.

To summarize the results of research question two, four of the nine warranted F-16 LRUs exhibited significantly greater reliability growths than their F-15 counterparts over the respective four year focal time periods. On the other hand, two non-warranted F-15 LRUs displayed greater growths than their warranted counterparts in the F-16. There was no statistical difference between the reliability growths observed for three of the LRU pairs. And finally, the reliability growth of the entire group of nine warranted LRUs was shown to be significantly greater than that of the entire group of nine non-warranted F-16 LRUs.

There were no striking differences between the results of this study, which covered a four year time span, and those of the ARINC interim evaluation, which covered a two year period. Their research also concluded that four warranted F-16 LRUs displayed higher growth rates. They did show, however, that there was no statistical difference between the reliability growths of the other five LRU pairs; they observed that none of the F-15 LRUs exhibited a statistically higher growth rate. The ARINC report concluded there was no difference between the growths of the RIW and Non-RIW "systems," which also contradicts the findings of this study. (29:2-19)

The results of this study suggest that one subcontractor, Westinghouse, the manufacturer of the fire control radar, was responsible for fielding a system that not only exhibited a greater MFHBF than its F-15 counterpart, but also surpassed the F-15 system in reliability growth over equivalent four year periods. All four of the warranted F-16 LRUs displaying significantly greater reliability growths were components of the Westinghouse radar. No other similar conclusions could be drawn about the other three subcontractors involved in the F-16 RIW.

IV. Conclusions and Recommendations

Summary

To successfully counter the perceived threat to our national security, the Department of Defense has acquired a succession of weapon systems, each of which is more complex and more costly than its predecessor. It is of utmost importance that military procurement agencies use the most cost effective "tools" available to them in the acquisition of these sophisticated systems. The reliability improvement warranty (RIW) is one such "tool" which has the potential for reducing a system's total life cycle costs. Unfortunately, very little research to determine the effectiveness of the RIW in DOD acquisition has surfaced. Therefore, the objective of this thesis was to investigate what effects, if any, a RIW had on the reliability of warranted avionics equipment. Specifically, this study was designed to answer the question of whether or not a warranted system was significantly more reliable than it would have been without the warranty. To accomplish this, the most comprehensive DOD application of RIW to date, the F-16 RIW, was investigated.

The thesis objective was attained by answering the two research questions, which formed the basic framework for the research effort:

1. As compared with the reliabilities (MTBFs) of nine functionally similar non-warranted line replaceable units

(LRUs) in the F-15, are the reliabilities of the nine F-16 warranted LRUs significantly higher?

2. As compared with functionally similar non-warranted LRUs in both the F-15 and F-16, did the nine F-16 warranted LRUs exhibit a significantly higher reliability growth during the first four years of operation?

The information used in the analysis was obtained from the Air Force Maintenance Data Collection System, or more specifically, the DO56 system. The data consisted of monthly failures and flight hours for each of the LRUs included in the study. To answer the first question, the entire third year after the start of production was used as a basis (1977 for the F-15 and 1981 for the F-16). Comparative four year periods were used as a basis for the second question (1975 to 1978 for the F-15 and 1979 to 1982 for the F-16). Chapter II contains a complete explanation of the research methodology employed to analyze the data and answer the two research questions. The reader should review the assumptions and limitations presented in that chapter, before accepting the findings and conclusions of this thesis. The conclusions apply only to the nine LRUs covered by the F-16 warranty; no attempt was made to generalize the results to equipment covered by other reliability improvement warranties.

Findings

Research Question One. As a result of the statistical comparisons, the answer to the first research question was an affirmative. The warranted F-16 LRUs, in general, demonstrated statistically greater reliability, as measured by mean flight hours between failures (MFHBFs), than the non-warranted F-15 LRUs. More specifically, of the nine warranted F-16 LRUs, six exhibited statistically greater third year MFHBFs than their F-15 counterparts, two exhibited statistically less reliability than the equivalent F-15 LRUs, and there was no difference in the reliability of one of the LRU pairs.

Research Question Two. The results of the statistical tests used to answer the second question were somewhat less conclusive than those used to answer the first. Four of the nine warranted F-16 LRUs exhibited statistically greater reliability growths than their F-15 counterparts over the respective four year focal time periods. Two displayed statistically less growth than their F-15 counterparts, and there was no statistical difference between the reliability growths observed for the remaining three LRU pairs. The second part of question two compared the reliability growth of the combined total of the entire group of nine warranted F-16 LRUs (defined as the RIW "system") with that of the combined total of a group of nine non-warranted F-16 avionics LRUs (Non-RIW "system"). The reliability growth of the RIW "system" was shown to be statistically greater than that of the Non-RIW "system." The evidence obtained in this study to answer the second research question was not convincing enough to give it either an affirmative or a negative answer.

Conclusions

While not overwhelming, there was a convincing degree of evidence that indicated the reliability of the warranted F-16 LRUs was greater than the reliability of functionally similar non-warranted F-15 LRUs. This study also concluded that the reliability growth rate of the warranted LRUs, taken as a group, was significantly greater than that of the non-warranted F-16 LRUs, taken as a group.

The next logical conclusion to make, then, would have been that the F-16 RIW program was the significant causal factor for this observed increase in reliability. Since this study was not specifically designed to make that inference, technically, that conclusion can not be drawn from the results. Harrison identified four conditions, however, that when met and the resultant action taken, would reasonably attribute an observed improvement in reliability to the RIW. The conditions are the following (29:2-1):

1. A desirable action is identified.

2. The action has clear economic advantages (to the contractor, assuming the contractor is motivated by profit.)

3. Risks are favorable with respect to economic returns.

4. There is opportunity to implement the action.

The first three, the contractor implicitly control; the last condition, the government controls, through its approval authority (29:2-1). There was no reason to believe the above four conditions were not present during the four year warranty period. That being the case, this study concluded that the observed increased reliability and reliablity growth rate of the warranted F-16 LRUs, was due, at least in part, to the F-16 reliability improvement warranty.

Recommendations for Future Research

Probably the area of recommended research that would provide the most significant impact, at least in relation to this thesis, would be a complete economic analysis of the F-16 RIW program, now that the program is concluded. According to the F-16 Program Office personnel responsible for closing out the program, no evaluation of the RIW cost impacts was ever undertaken. An ARINC Research Corporation interim report did provide an extensive economic evaluation of the F-16 RIW; however, that evaluation was based on data from the first two years of the warranty, which really represented less than one fourth of the actual accrued flying time for the entire warranty period. Since this has been the most extensive DOD use of a warranty to date, an exhaustive economic evaluation of this program would certainly be in order.

Additionally, parallel research efforts should be performed to evaluate the effectiveness, in terms of reliability improvement and costs, of other Air Force warranty programs, as well as the warranty programs of the other military services.

APPENDIX A: Flight Hours And Failure Data

Source: LOG-MMO(AR)7170 / LOG-LOE(AR)7170 monthly reports, from 31 January 1975 to 31 December 1982.

TABLE XII

F-15 FLEET MONTHLY FLIGHT HOURS FROM 1975-1978

	1975	1976	1977	1978
Jan	93	636	2469	3844
Feb	87	718	2589	4262
Mar	167	928	3259	5549
Apr	194	968	2103	5159
May	244	1023	4183	5852
Jun	320	1169	3925	6486
Jul	257	2359	2431	5158
Aug	326	1660	4525	7047
Sep	238	1795	3719	6320
Oct	511	1787	4061	6593
Nov	322	2260	5202	6187
Dec	495	2286	3844	6057

TABLE XIII

F-16 A/B FLEET MONTHLY FLIGHT HOURS FROM 1979-1982

	1979	1980	1981	1982
Jan	172	1161	3670	6916
Feb	181	1424	3505	7425
Mar	223	1589	5694	9140
Apr	299	1783	5874	7993
May	371	2370	6266	8448
Jun	410	1917	5944	8526
Jul	474	2366	5835	8701
Aug	479	2493	1344	9805
Sep	779	2276	4734	8714
Oct	1095	3269	6264	10371
Nov	1069	2927	6467	10238
Dec	955	2824	5821	9774

TABLE XIV

F-15 LRU MONTHLY FAILURES FOR 1975

	52AAO 52ABO	74FUO	74FCO	74FAO	74FFO	74FQO	74KAO	74KCO	71AEO
Jan	0	0	2	0	3	2	5	3	12
Feb	0	1	0	0	1	1	0	0	5
Mar	0	0	1	3	2	1	1	4	8
Apr	0	4	0	6	2	1	6	2	2
May	1	4	2	1	5	4	2	3	11
Jun	0	5	1	5	8	3	1	2	3
Jul	0	8	2	1	8	10	3	4	9
Aug	2	7	1	9	12	11	2	5	15
Sep	2	12	6	5	9	9	6	5	25
Oct	4	5	2	10	7	13	10	5	18
Nov	3	9	6	10	6	10	4	3	11
Dec	8	6	5	15	4	12	4	9	11

TABLE XV

F-15 LRU MONTHLY FAILURES FOR 1976

	52AAO 52ABO	74FUO	74FCO	74FAO	74FFO	74FQO	74KAO	74KCO	71AEO
Jan	5	10	3	12	10	13	4	9	13
Feb	5	6	3	13	13	19	5	4	20
Mar	10	12	11	12	16	10	5	12	20
Apr	5	17	8	13	16	8	5	12	25
May	10	17	13	24	16	17	11	8	22
Jun	6	10	5	22	10	18	9	8	12
Jul	2	15	10	21	9	18	7	8	16
Aug	4	15	30	29	23	26	5	12	27
Sep	3	19	22	30	15	21	12	12	17
Oct	4	15	2	21	15	25	7	7	28
Nov	2	18	13	25	15	30	13	20	27
Dec	9	7	12	21	22	35	9	16	28

TABLE XVI

F-15 LRU MONTHLY FAILURES FOR 1977

	52AAO 52ABO	74FUO	74FCO	74FAO	74FFO	74FQO	74KAO	74KCO	71AEO
Jan	3	23	25	30	31	34	22	27	42
Feb	2	23	17	28	27	44	15	15	41
Mar	3	15	21	18	18	21	13	7	29
Apr	3	13	9	16	18	18	10	4	16
May	2	27	20	29	24	26	32	13	30
Jun	12	26	17	20	31	26	26	9	31
Jul	10	22	25	20	31	27	18	16	42
Aug	18	43	30	34	45	57	27	25	39
Sep	16	36	14	44	30	42	21	15	35
Oct	21	30	37	59	37	54	23	22	45
Nov	18	25	34	49	41	40	25	10	38
Dec	17	24	36	45	35	34	17	9	39

TABLE XVII

F-15 LRU MONTHLY FAILURES FOR 1978

	52AAO 52ABO	74FUO	74FCO	74FAO	74FFO	74FQO	74KAO	74KCO	71AEO
Jan	11	20	19	27	26	35	28	13	33
Feb	12	23	43	47	32	44	42	9	51
Mar	13	20	49	58	36	44	32	8	42
Apr	13	47	28	53	34	32	22	16	46
May	17	54	39	48	33	45	20	13	43
Jun	16	45	37	66	27	56	30	24	42
Jul	12	45	24	49	20	34	32	26	63
Aug	11	41	27	47	16	43	34	21	34
Sep	21	46	47	54	42	46	28	19	54
Oct	12	57	38	66	28	50	19	21	65
Nov	15	39	28	54	19	30	24	8	47
Dec	20	47	31	75	31	51	22	11	60

TABLE XVIII

F-16 RIW LRU MONTHLY FAILURES FOR 1979

	14AAO	74AAO	74ABO	74ACO	74ADO	74AFO	74BAO	74BCO	74DAO
Jan	0	0	0	0	0	0	0	0	0
Feb	0	4	2	0	0	1	2	4	4
Mar	2	6	1	0	1	1	1	0	1
Apr	0	3	7	6	1	4	4	0	2
May	0	2	2	2	1	2	4	1	3
Jun	1	9	9	10	3	10	5	0	13
Jul	1	2	5	6	1	7	2	0	5
Aug	7	5	9	9	5	6	4	3	7
Sep	3	7	10	11	10	14	4	5	9
Oct	3	10	9	8	5	12	4	1	5
Nov	11	10	16	16	5	10	8	2	5
Dec	7	19	34	17	6	12	4	3	14

TABLE XIX

F-16 RIW LRU MONTHLY FAILURES FOR 1980

	14AAO	74AAO	74ABO	74ACO	74ADO	74AFO	74BAO	74BCO	74DAO
Jan	4	9	13	14	0	15	1	1	14
Feb	12	21	14	13	8	15	8	2	7
Mar	7	15	16	16	9	14	7	4	22
Apr	3	25	11	16	10	9	2	2	13
May	16	20	9	9	7	12	2	6	27
Jun	12	8	9	8	7	12	7	6	13
Jul	9	13	14	9	10	12	10	10	18
Aug	11	20	17	23	5	9	9	7	28
Sep	7	17	15	12	8	6	7	5	23
Oct	7	17	15	9	6	6	13	7	24
Nov	13	22	18	16	10	14	12	3	29
Dec	6	20	20	13	8	9	9	6	19

TABLE XX

F-16 RIW LRU MONTHLY FAILURES FOR 1981

	14AAO	74AAO	74ABO	74ACO	74ADO	74AFO	74BAO	74BCO	74DAO
Jan	9	25	27	10	5	12	16	7	32
Feb	20	39	31	18	15	11	16	4	34
Mar	15	33	32	20	17	9	12	4	53
Apr	7	43	33	23	17	18	21	12	27
May	22	34	41	22	15	11	17	7	42
Jun	11	44	26	22	15	23	13	5	34
Jul	21	46	19	9	19	14	15	8	43
Aug	14	45	23	14	6	13	11	7	25
Sep	14	43	29	22	13	13	9	5	23
Oct	12	44	43	26	13	17	18	9	47
Nov	23	26	39	12	11	6	22	5	47
Dec	7	24	32	21	11	9	11	7	53

TABLE XXI

F-16 RIW LRU MONTHLY FAILURES FOR 1982

	14AAO	74AAO	74ABO	74ACO	74ADO	74AFO	74BAO	74BCO	74DAO
Jan	12	35	35	28	16	20	18	11	44
Feb	7	36	25	19	15	10	15	6	29
Mar	19	23	35	23	8	11	12	13	37
Apr	20	53	55	29	19	30	12	16	56
May	24	33	39	19	10	6	20	13	48
Jun	24	33	34	23	13	19	26	6	47
Jul	58	69	68	53	21	32	39	25	63
Aug	22	36	47	19	9	24	23	22	59
Sep	19	43	45	29	14	20	25	21	45
Oct	24	52	49	42	25	15	32	17	68
Nov	31	32	49	26	12	22	29	19	63
Dec	32	32	46	31	10	16	34	11	51

TABLE XXII

F-16 RIW LRU MONTHLY FAILURES - COMBINED TOTAL
(1979-1982)

	1979	1980	1981	1982
Jan	0	71	143	219
Feb	17	100	188	162
Mar	13	110	195	181
Apr	27	91	201	290
May	17	108	211	212
Jun	60	82	193	225
Jul	29	105	194	428
Aug	55	129	158	261
Sep	73	100	171	261
Oct	57	104	229	324
Nov	83	137	191	283
Dec	116	110	175	263

TABLE XXIII

F-16 NON-RIW LRU MONTHLY FAILURES - COMBINED TOTAL
(1979-1982)

	1979	1980	1981	1982
Jan	0	35	46	88
Feb	2	28	70	76
Mar	11	53	88	99
Apr	13	45	86	172
May	5	41	84	122
Jun	18	36	77	122
Jul	25	59	85	291
Aug	13	69	61	119
Sep	29	29	71	142
Oct	20	46	95	148
Nov	46	55	67	159
Dec	64	46	94	163

APPENDIX B: Critical F Value Approximation

Since percentage points of the F distribution tables (F tables) only tabulate critical F values for degrees of freedom up to 120, the following approximation formula, from Applied Statistics - A Handbook of Techniques, by Lothar Sachs, was used (55:151):

$$\log F = (0.4343)\ (z) \left[\sqrt{\frac{2(\gamma_1 + \gamma_2)}{\gamma_1 \gamma_2}} \right] \tag{13}$$

where z is the standard normal value for the chosen significance level of a one-sided test and γ_1 and γ_2 are the numerator and denominator degrees of freedom, respectively.

For example, the approximate value of $F\ (348,\ 248;\ .05)$ is given by

$$\log F = (0.4343)\ (1.645) \left[\sqrt{\frac{2(348+248)}{(348)(248)}} \right] = 0.0840$$

$$F = 10^{.0840} = 1.213$$

Bibliography

1. Brabson, Col G. Dana. "The Defense Acquisition Improvement Program," Program Manager, 12: 5-13 (November-December 1983).

2. Beck, Alan W. "Warranties: A Few Basics on the Latest Hot Topic," Program Manager, 13: 9,10 (March-April 1984).

3. Brown, Tom, Deputy Director. Personal interview. Air Force Acquisition Logistics Center / Product Performance Agreement Center, Wright-Patterson AFB OH, 18 October 1984.

4. Kozicharow, Eugene. "Pentagon Asks Change in Weapons Guarantees," Aviation Week and Space Technology, 120: 14-16 (April 2, 1984).

5. Flora, Whitt. "Defense Department Proposing Warranty Mandate Repeal," Aviation Week and Space Technology, 120: 44 (February 20, 1984).

6. Black's Law Dictionary (Fifth Edition). St. Paul MN: West Publishing Company, 1979.

7. Department of Defense, General Services Administration, and National Aeronautics and Space Administration. Federal Acquisition Regulation (FAR). Washington: Government Printing Office, 1984.

8. Air Force Logistics Command. Product Performance Agreement Guide. Unpublished Pamphlet. Wright-Patterson AFB OH, 22 July 1980.

9. Gilleece, Mary Ann. "The Warranty Tool," Defense 84, 25-28 (February 1984).

10. Harrison, G. F-16 Reliability Improvement Warranty Implementation and Management Plan. ARINC report, 1565-21-1-2461. ARINC Research Corporation, Annapolis MD, May 1981 (AD-A099 303).

11. Department of the Air Force, DCS/Systems and Logistics, Directorate of Procurement Policy (AF/LGP). Interim Guidelines - Reliability Improvement Warranty (RIW). Washington: Government Printing Office, July 1974.

12. Parkinson, Capt David R., and Capt Alan W. Schoolcraft. An Evaluation of the Perceived Effectiveness of Reliability Improvement Warranties (RIW) Applied During the Air Force RIW Trial Period. MS thesis, LSSR 58-83. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1983 (AD-A134 361).

13. Trimble, Robert F. "Can Contract Methodology Improve Product Reliability?" Defense Management Journal, 12: 20-23 (April 1976).

14. Balaban, Harold S., and Bernard L. Retterer. Guidelines for Application of Warranties to Air Force Electronic Systems. ARINC report, RADC-TR-76-32. ARINC Research Corporation, Annapolis MD, March 1976 (AD-A023 956).

15. Balaban, Harold S. "Reliability Improvement by Profit Incentive," Quality, 17: 22-28 (November 1978).

16. Gandara, Arturo, and Michael D. Rich. Reliability Improvement Warranties for Military Procurement. Rand report, R-2264-AF. Rand Corporation, Santa Monica CA, December 1977 (AD-A055 904).

17. Hudkins, Maj Raymond P. Reliability Improvement Warranties: An Analysis of Contractor Incentives and Risks. Research Report, 1090-78. Air Command and Staff College (AU), Maxwell AFB AL, May 1978 (AD-B028 820).

18. Tucker, Capt Michael P. In Defense of the RIW. Unpublished research report. U.S. Army Logistics Management Center (Florida Institute of Technology), Fort Lee VA, 2 June 1980.

19. Amstadter, Bertram L. Reliability Mathematics. New York: McGraw-Hill Book Company, 1971.

20. DeMarchi, Capt Daniel. A Case Study of Reliability and Maintainability of the F-16 APG-66 Fire Control Radar. MS thesis, LSSR 99-81. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1981 (AD-A111 387).

21. Department of Defense. Reliability Growth Testing. MIL-STD-1635(EC). Washington: Government Printing Office, 3 February 1978.

22. MacDiarmid, Preston R. and Seymour F. Morris. Reliability Growth Testing Effectiveness. In-House Report, RADC-TR-84-20. Rome Air Development Center, Griffis AFB NY, January 1984 (AD-A141 232).

23. Gates, Robert K. and others. "Quantitative Models Used in the RIW Decision Process," Proceedings Annual Reliability and Maintainability Symposium. 229-236. Institute of Electrical and Electronics Engineers, Inc., New York, January 1977.

24. Mills, Maj Bruce D. The Use of Warranties in the Acquisition of Conventional Munitions. Research Report, 1725-81. Air Command and Staff College (AU), Maxwell AFB AL, May 1981 (AD-B057 697L).

25. Hellesto, Capt Greg T., and Capt Michael G. Oliverson. Cost Analysis of Turbine Engine Warranties. MS thesis, LSSR 85-82. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1982 (AD-A123 034).

26. Klass, Philip J. "Users, Sellers Study Warranty Lessons," Aviation Week and Space Technology, 118: 103-107 (January 10, 1983).

27. "The Warranty Law," Air Force Magazine, 67: 22 (November 1984).

28. Bowling, Carolyn A., Contracting Officer. Personal interview. F-16 Program Office, Aeronautical Systems Division (AFSC), Wright-Patterson AFB OH, 30 January 1985.

29. Harrison, George. An Interim Evaluation of the F-16 Reliability Improvement Warranty (RIW) Program. ARINC report, 1565-11-2-2527. ARINC Research Corporation, Annapolis MD, September 1981.

30. Department of Defense. Definitions of Terms for Reliability and Maintainability. MIL-STD-721C. Washington: Government Printing Office, June 1981.

31. Department of the Air Force. Compendium of Authenticated Systems and Logistics Terms, Definitions and Acronyms. Wright-Patterson AFB OH: School of Systems and Logistics, Air Force Institute of Technology (AU), 1981.

32. Air Force Logistics Command. Maintenance Actions, Man-Hours, and Aborts by Work Unit Code. Unpublished pamphlet No. Q-DO56B-B06-RX-254. Wright-Patterson AFB OH, 7 November 1982.

33. Jane's All the World's Aircraft 1984-85, edited by John W. R. Taylor. New York: Janes Publishing Inc., 1984.

34. Morris, Ronald S. and Bruce E. Bartels. "Determining Operating and Support Costs with USAF DO56 Maintenance Data Collection System," Proceedings Annual Reliability and Maintainability Symposium. 197-206. Institute of Electrical and Electronics Engineers, Inc., New York, January 1984.

35. Goree, Paul F. F-15 AN/APG-63 Radar Reliability and Maintainability Case Study Report. Contract MDA-903-79-C-0018. Institute for Defense Analyses, Alexandria VA, August 1983 (AD-A142 071).

36. Boiles, John H. and John J. Hadel. "Reliability Growth Measured by AFM 66-1 Data," Proceedings Annual Reliability and Maintainability Symposium. 465-471. Institute of Electrical and Electronics Engineers, Inc., New York, January 1981.

37. Gross, Chuck. Quick Reference Guide to Maintenance Data Collection (MDC). Unpublished pamphlet, MME-2. Air Force Logistics Command, Wright-Patterson AFB OH, 1984.

38. Baldrige, Capt Jeffrey W. and Lt James F. Kenney. Effect of Maintenance Actions on the Reliability of Four Line Replaceable Units in the A-7 Aircraft. MS thesis, SLSR 18-76B. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1976 (AD-B015 220).

39. Department of the Air Force. F-16A Work Unit Code Manual. T.O. 1F-16A-06. Washington: HQ USAF, 24 October 1983.

40. Department of the Air Force. F-15A Work Unit Code Manual. T.O. 1F-15A-06. Washington: HQ USAF, 1 July 1982.

41. ARINC Research Corporation. Reliability Engineering, edited by William H. Von Alven. Englewood Cliffs NJ: Prentice-Hall, Inc., 1965.

42. Kapur, K. C. and L. R. Lamberson. Reliability in Engineering Design. New York: John Wiley and Sons, 1977.

43. McClave, James T. and P. George Benson. Statistics for Business and Economics (Second Edition). San Francisco: Dellen Publishing Company, 1982.

44. Mann, Nancy R. and others. Methods for Statistical Analysis of Reliability and Life Data. New York: John Wiley and Sons, 1974.

45. Hardy, C. A. and R. J. Allen. "Reliability Improvement Warranty Techniques and Applications," Proceedings Annual Reliability and Maintainability Symposium. 222-228. Institute of Electrical and Electronics Engineers, Inc., New York, January 1977.

46. Bauman, Michael F. A Comparative Analysis of Reliability Growth Models. USAMC-ITC Report No. 1-73-01. U. S. Army Logistics Management Center, Intern Training Center, Texarkana TX, May 1973 (AD-768 119).

47. Department of Defense. Reliability Growth Management. MIL-HDBK-189. Washington: Government Printing Office, 13 February 1981.

48. VonLoh, Capt John F. Reliability Growth and Its Applications to Dormant Reliability. MS thesis, AFIT/GOR/MA/81D-12. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, December 1981.

49. Koo, David. "Growth Test Time - Key to Effective Test Planning," Proceedings Annual Reliability and Maintainability Symposium. 389-394. Institute of Electrical and Electronics Engineers, Inc., New York, January 1981.

50. Crow, Larry H. "On Tracking Reliability Growth," Proceedings Annual Reliability and Maintainability Symposium. 438-442. Institute of Electrical and Electronics Engineers, Inc., New York, January 1975.

51. Crow, Larry H. "Reliability Analysis for Complex, Repairable Systems," Reliability and Biometry, edited by Frank Proschan and R.J. Serfling. Society for Industrial and Applied Mathematics, Philadelphia, 1974.

52. Ascher, Harold E. "Weibull Distribution vs Weibull Process," Proceedings Annual Reliability and Maintainability Symposium. 426-431. Institute of Electrical and Electronics Engineers, Inc., New York, January 1981.

53. Atkinson, Kendall. Elementary Numerical Analysis. New York: John Wiley and Sons, 1985.

54. Air Force Logistics Command. "Maintenance Actions, Manhours, and Aborts by Work Unit Code," Unpublished monthly reports, LOG-MMO(AR)7170 / LOG-LOE(AR)7170. Wright-Patterson AFB OH, 31 January 1975 to 31 December 1982.

55. Sachs, Lothar. Applied Statistics - A Handbook of Techniques. New York: Springer-Verlag, 1984.

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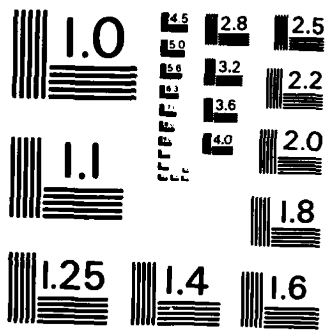

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Professor of Government Contract Law

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This investigation examined the effects a reliability improvement warranty (RIW) had on the actual operational reliability of the warranted avionics equipment. To accomplish this, the most comprehensive DOD application of RIW to date, the F-16 RIW, was investigated. This study was designed to answer the question of whether or not a warranted system was significantly more reliable than it would have been without the warranty. Specifically, the observed mean flight hours between failures (MFHBFs) and the observed reliability growths of the warranted F-16 equipment were compared to those of functionally similar non-warranted F-15 equipment. Also, the reliability growth of the F-16 warranted equipment was compared to that of other non-warranted F-16 equipment. The AMSAA Reliability Growth Model was used as a basis for the reliability growth analyses. Comparable life cycle time periods for each aircraft were studied, using AFM 66-1 DO56 failure and flight time data.

The results of the investigation indicated that, in general, the observed MFHBFs of the F-16 warranted equipment were statistically greater than the MFHBFs of the equivalent F-15 equipment. The same could not be concluded for the reliability growths of the F-16 and equivalent F-15 equipment. However, the reliability growth of the warranted F-16 equipment was found to be statistically greater than the reliability growth of the non-warranted F-16 equipment. The study concluded that the observed increased reliability and reliability growth rate of the warranted F-16 equipment, was due, at least in part, to the F-16 RIW.

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